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THE EFFECT OF HOLE GEOMETRY ON DISCHARGE COEFFICIENT OF ROTATING AXIAL HOLES UNDER PRE-SWIRL CONDITIONS

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ABSTRACT

With the rapid development of gas turbines, the temperature in it, especially at the inlet of the turbine, is getting higher and higher. To ensure the life and safety of gas turbines, the functions of cooling and sealing of the secondary air system are getting more and more important. Axial rotating holes have been used widely in the secondary air system to transport cooling and sealing air. The rotational effect and Coriolis force strongly influence the aerodynamic performance of flow through rotating holes. The current paper investigates the flow with and without pre-swirl through two types of axial holes (round and square in cross-sectional shape respectively) in rotating disks at various flow conditions using both experiment and CFD methods. A test rig with equipment which can adjust pre-swirl angle of incoming flow smoothly has been introduced. Different pre-swirl angles (from 0 to 60 °) are used to simulate the flow influenced by upstream components in real gas turbines. The study includes the flow phenomena and the discharge coefficients of these holes under different pressure ratio (from 1.02 to 1.3) and rotating speed (from 0 to 9000 rpm). The discharge coefficients (C_d) of axial rotating holes in a relative frame of reference have been obtained. It shows that square holes provide a superior discharge coefficient than round holes. The application of square holes is good for improving flow efficiency, especially under high rotating speed conditions.

INTRODUCTION

Rotating holes are widely used in the secondary air system in gas turbines. Determining moderate cooling air through rotating holes is crucial to provide a safe operating condition without having a detrimental effect on the performance of the system. As a consequence, having a comprehensive understanding of the flow phenomenon and flow characteristics through rotating axial holes in rotating discs and shafts is crucial.

Hay (Hay 1998) gave a detailed review of the influencing factors of the discharge coefficient of stationary holes in 1998. The factors can be divided into geometry parameters and flow parameters. "Rotation of the hole" was mentioned as one of the flow parameters which could strongly influence the flow characteristics of rotating holes. However, almost no relevant experiments were carried out then, and it was impossible to give a specific relationship between discharge coefficient and rotation.

The incoming flow of receiver holes in the secondary air system is always under pre-swirl conditions. This phenomenon is sometimes caused by upstream components, and sometimes it is made intentionally. By accelerating the cooling air in rotating direction, the total temperature relative to the rotor disk and the losses in pressure of cooling air can be reduced. As is investigated in the past (Javiya 2011), the total temperature reduction can be up to 20K due to pre-swirl. The earliest study of pre-swirl of incoming flow was by

Dittmann in 2001, which showed a close relationship between discharge characteristic and pre-swirl condition (Dittmann 2001). Idris investigated the effect of pre-swirl on the discharge coefficient of rotating axial holes, which showed that pre-swirl tends to increase the discharge coefficient for inclined holes (Idris 2006).

The previous study concerned the discharge coefficient in an absolute frame of reference. However, it was found that the discharge coefficient in an absolute frame of reference would build up to 1 due to the neglect of work transferred from rotating disc to flow passed through the hole. To constrain C_d between 0 and 1, Zimmermann proposed to use parameters in a relative frame of reference (Zimmermann 1998). The parameter used to represent discharge coefficient is velocity ratio (U/C_{id}) and velocity head ratio ($\Theta_v = (p_{t,rel} - p_2)/(p_{t,rel} - p_1)$, for conditions with cross-flow, Alexiou 2000). However, Idris indicated that the parameter U/C_{id} has some disadvantages in representing C_d , such as the disability to describe the direction of the inlet flow (Idris 2004). Thus these parameters are not suitable for cases under pre-swirl conditions. Idris proposed incidence angle i as a good parameter to correlating C_d , especially for holes with high rotating speed and angle of inclination.

As is known to the author, the investigation of holes with different cross-sectional shapes is much less, and the study of discharge characteristic of square holes under pre-swirl and rotating conditions is completely absent.

EXPERIMENTAL APPARATUS

The test rig at Institute of Engineering Thermophysics, Chinese Academy of Sciences is now using to investigate the flow characteristics of different types of holes under different flow and rotating conditions. The line drawing of the test rig is shown in Fig. 1, while the schematic drawing of the test rig is shown in Fig.2. A screw compressor with air cooling and drying equipment produces required high pressure air for the experiments and provides the test rig with requested operating conditions. The volume flow rate of compressed air is measured by a vortex flowmeter (DN 125mm) capable of measuring airflow up to 1700 m³/h. Two platinum resistance thermometers are used to measure air temperature. All data of flow and temperature is collected by ADAM-4117 and transferred to PC.

A dedicated electronic barometer is employed to measure pressure in atmosphere. Pressure sensors (piezoresistive strain gauge) are used to measure static pressure through holes on external casing. Three-hole probes (three on different axial positions) are used to measure flow field upstream and downstream of the rotating holes. The uniformity of flow field is verified by three measuring points located uniformly along a circumferential direction, which is important to the validity of data.

The motor used to drive the rotor have a power output of 25 kW with a rated rotating speed of 14600 rpm. Rotating speed is controlled by VFD 370B43A. A flexible diaphragm

coupling connects the motor and load (rotating disc). The max rotating speed in this experiment is 9000 rpm.

Fig. 1 line drawing of the test rig

Fig. 2 schematic drawing of the test rig

An air intake cone located in air inlet region (shown in Fig. 2) uniforms incoming flow. A set of full-circle pre-swirl guide vanes (Fig. 3) located upstream of the rotating disc creates the pre-swirl angle of incoming flow from 0-60°. The setting angle of guide vanes can be changed artificially by an actuator. The air downstream of the rotating disc is exhausted upward in air through a volute.

Fig.3 guide vanes upstream of the rotating disk

Fig. 4 shows the dimension of the rotating disc. Two types of holes (square and round) with a same cross-sectional area

are shown in Fig. 5. The diameter of the round hole is 18 mm while the length is 9 mm, with a L/d ratio of 0.5. The rotating disc with square holes and two probes in different circumferential directions is shown in Fig. 6.

Fig. 4 dimension of the rotating disc (mm)

Fig. 5 dimension of the square hole (left) and the round hole (right) (mm)

Fig. 6 rotating disc with square holes

DATA ANALYSIS

The discharge characteristics of flow through rotating axial holes is usually quantified by discharge coefficient, C_d ,

which is the ratio of actual mass flow rate divided by the flow rate for ideal case. The current paper use discharge coefficient in a relative frame of reference (equation 1) in order to limit $C_{d,rel}$ between 0 and 1. The actual mass flow rate can be measured experimentally, while the ideal mass flow rate in relative frame is calculated by equation 2.

$$C_{d,rel} = \frac{m}{m_{id,rel}} \quad (1)$$

$$m_{id,rel} = A \frac{p_{1,rel,tol}}{RT_{1,rel,tol}} \left(\frac{p_2}{p_{1,rel,tol}} \right)^{1/k} \sqrt{\frac{2k}{k-1} RT_{1,rel,tol} \left[1 - \left(\frac{p_2}{p_{1,rel,tol}} \right)^{(k-1)/k} \right]} \quad (2)$$

The static pressure at hole outlet (p_2) in equation 2 can be measured by three-hole probe, while total temperature and total pressure at hole inlet in relative frame are calculated by equation 3 and 5.

$$T_{1,rel,tol} = T_{1,tol} + \frac{v_{1,x}^2 + (v_{1,\phi} - U)^2 - v_1^2}{2c_p} \quad (3)$$

$$T_{1,tol} = T_1 + \frac{v_1^2}{2c_p} \quad (4)$$

$$p_{1,rel,tol} = p_1 \left(\frac{T_{1,rel,tol}}{T_1} \right)^{k/(k-1)} \quad (5)$$

The velocity triangles of rotating axial holes are shown in Fig. 7. $U+v_\phi$ is the relative velocity of flow to rotating disk in a circumferential direction. $C_{id,rel}$ is the relative velocity of flow to rotating disk in an axial direction, which is calculated by equation 6. W is the relative velocity of flow getting into the rotating hole. The value of $(U+v_\phi)/C_{id,rel}$ is the tangent of inlet velocity angle (incidence angle) i in relative frame, which is calculated by equation 7. In previous studies (Sousek 2014), the discharge coefficient reaches the maximum value when i approaches 0, in which case flow approaches hole inlet directly along the axial direction.

Fig. 7 velocity triangles at hole inlet

$$C_{id,rel} = \sqrt{\frac{2k}{k-1} RT_{1,rel,tol} \left[1 - \left(\frac{p_2}{p_{1,rel,tol}} \right)^{(k-1)/k} \right]} \quad (6)$$

$$i = \tan^{-1}((U + v_\phi) / C_{id,rel}) \quad (7)$$

CFD METHOD AND MODEL

The commercial CFD codes ANSYS CFX 19.0 is used in the CFD process. Fig. 8 shows a typical mesh for rotating axial holes, which is generated by ANSYS ICEM CFD 19.0. All the CFD simulations are under steady condition.

Total pressure and total temperature are specified at hole inlet and average static pressure is specified at hole outlet of the model. Only a 14.4 deg sector (1/25 of the disk used in experiments) is simulated due to the symmetry hypothesis between different sections. In order to maintain a continuous flow field, the rotational periodic boundary is used. For a more efficient simulation of flow through rotating holes, the whole domain is set to be rotating at a constant speed, and counter-rotating wall is specified as boundary condition at up and down walls.

Fig. 8 CFD domain and mesh

Fig. 9 shows the mesh cut plane of round and square holes. The thickness of the first layer near the wall is set to be $10e-6$ m to restrict y^+ to 1 or less. The mesh quality (determinant $2*2*2 \geq 0.6$) in ICEM.

Fig. 9 mesh cut plane of holes

In order to get a mesh-independent result, the mesh is refined until the CFD results stop to change with the increase of number of mesh elements, shown in Fig. 10. Finally the mesh number is set to 750000.

SST and k- ϵ turbulence models are commonly used in flow simulation of rotating systems. These two models are compared with experimental data (velocity at hole inlet under 0 pre-swirl 8000rpm conditions), and the results are shown in Fig. 11. It shows that SST model fits experimental data better than k- ϵ model, so SST model is more suitable to simulation of flow through rotating holes.

Fig. 10 mass flow rate values with mesh elements

Fig. 11 turbulence model comparison and validation

The experimental and CFD results are compared in Fig. 12, which shows a good agreement. The error bars of experimental results include the error caused by measurement (temperature, flow rate and pressure) and calculation (static and total parameters in relative frame of reference). The overall error of these experimental results is about 6.7%, which shows that the experimental results is acceptable and credible.

Through the analysis of CFD results, the flow field around the hole can be analysed in detail to explore the mechanism that varies the discharge coefficient due to different hole geometries.

Fig. 12 compare experiment with CFD results

RESULTS AND DISCUSSION

The effect of rotating speed and pressure ratio

The pre-swirl angle of incoming flow is usually large in secondary air system due to the influence of upstream components. Therefore, CFD cases under high pre-swirl angle of 60 deg are taken into account.

Table 1 CFD cases

Pre-swirl (deg)	Rotating speed (rpm)	Pressure ratio		
		1.02	1.15	1.3
60	0	1.02	1.15	1.3
	4000	1.02	1.15	1.3
	8000	1.02	1.15	1.3

The $C_{d,rel}$ with different pressure ratio in relative frame under different rotating speeds are shown in Fig. 13, 14 and 15 respectively. The discharge coefficients of both round and square hole are greatly influenced by pressure ratio and rotating speed. $C_{d,rel}$ increases with increasing pressure ratio and decreases with increasing rotating speed, the gradient of $C_{d,rel}$ with pressure ratio is increasing greatly with increasing rotating speed. As the pressure ratio increases from 1.02 to 1.3, the increase of $C_{d,rel}$ is 7.35% and 77.66% for the case that is stationary and 8000 rpm respectively. That means $C_{d,rel}$ is more sensitive to pressure ratio under high rotating speed conditions. And for all these three cases, square hole provides a superior discharge coefficient than round one.

In order to investigate the effect of rotating speed on discharge coefficient of rotating holes in detail, total pressure and streamline of two cases are shown in Fig. 16 & 17 (left: round hole-60 preswirl-stationary-1.15 pressure ratio; right: round hole-60 preswirl-8000rpm-1.15 pressure ratio). In stationary case, there is a large proportion of area with high total pressure in the hole, which means a large area of flow with high speed. As for the case of 8000 rpm, the total pressure in the hole is much lower, and there is a large region of separation and a large scale of vortex at the entrance of the hole, which is shown by streamline in Fig. 17. The complex structure of vortex makes the flow field more complicated, and

the effective flow area of the hole is greatly reduced, which can attribute to the decrease of discharge coefficient under rotating conditions.

Fig. 13 CFD results-stationary

Fig. 14 CFD results -4000 rpm

Fig. 15 CFD results -8000 rpm

Fig. 16 total pressure on middle longitudinal section of the hole in different rotating speed (left-stationary ; right-8000rpm)

Fig. 17 total pressure and streamline on middle cross section of the hole in different rotating speed (left-stationary ; right-8000rpm)

The effect of hole geometry

Fig. 13, 14 and 15 show the difference in discharge coefficient between round and square holes. The difference becomes larger with the increase of rotating speed, and is more obvious in the cases of high rotating speed and high pressure ratio.

In order to consider the influence of pressure ratio, rotating speed and pre-swirl of incoming flow uniformly, the discharge coefficient is correlated with incidence angle (i). The data of round and square holes are all shown in Fig. 18, and the relationship between incidence angle and discharge coefficient of two types of holes are obtained by the method of polynomial fitting respectively. Square hole has a higher discharge coefficient than round hole at the same incidence angle.

Fig. 19 (left: round hole-60 preswirl-8000rpm-1.15 pressure ratio; right: square hole-60 preswirl-8000rpm-1.15 pressure ratio) can give an explanation to this phenomenon. At the same incidence angle, there is a larger proportion of separation region in round hole, which makes the effective flow area smaller and the discharge coefficient lower than case of square hole. This is because the circumferential length of square hole is larger than that of round hole under a same cross-sectional area, which makes the square hole easier to intake air in a circumferential direction, especially under high rotating speed conditions.

Fig. 18 $C_{id,rel}$ curve with incidence angle for square and round holes

Fig. 19 total pressure and streamline on middle cross section of the hole in different hole geometry (left-round ; right-square)

CONCLUSIONS

The discharge coefficient of both round and square holes decrease with the increase of incidence angle. The square holes provide a superior discharge coefficient than round holes. This study is useful for designing a high performance hole in gas turbine secondary air systems.

1. A test rig of discharge characteristics of rotating axial holes with adjustable pre-swirl angle of incoming flow is introduced, as well as the measurement and data processing method.

2. The discharge coefficients of rotating holes (round and square) increase with the increase of pressure ratio, and decrease with the increase of rotating speed.

3. The effects of pre-swirl of incoming flow and rotating speed of holes can be reflected in the parameter of incidence angle.

4. The square hole has a higher discharge coefficient than round hole, especially in the cases of high rotating speed. This phenomenon is attributed to the different condition of flow separation at inlet of the hole. It provides a new idea for the optimal design of the secondary air system of gas turbines.

NOMENCLATURE

A	= cross-sectional area of a hole
C_d	= discharge coefficient
L	= hole length
D	= hole diameter
m	= mass flow rate
U, n, ω	= rotating speed of a hole (the unit is m/s, rpm, rad/s respectively)
p	= pressure
R	= specific gas constant
C_p	= specific heat capacity at constant pressure
T	= temperature
v	= velocity of flow
γ	= isentropic exponent
ρ	= density of flow
Π	= pressure ratio
θ	= pre-swirl angle of incoming flow
i	= incidence angle
act, id	= actual, ideal parameter respectively
abs, rel	= absolute, relative frame of reference respectively
tol	= total parameter
x, ϕ, r	= axial, circumferential, radial coordinate respectively
1,2	= upstream, downstream of a hole respectively
rot, sta	= rotating, stationary condition respectively

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